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A MOBILITY CONCEPT FOR MARTIAN EXPLORATION

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ABSTRACT

Soil mechanics and geological investigations on Mars or the Moon are described herein, using a novel mobility system, designated as the "Elastic Loop Mobility System (ELMS)". ELMS was developed as a spin-off of the U.S. Lunar Roving Vehicle (LRV) which operated on the Moon during the Apollo 15, 16, and 17 Missions.

Extensive testing of the ELMS, both on soft soil and on rigid obstacles, has shown that the ELMS outperforms by far both the LRV and the two unmanned, self-propelled Soviet rovers, Lunokhod 1 and 2, which landed on the Moon in the western part of Mare Imbrium, aboard the spacecraft Luna 17 and 21. In this paper, examples of soil mechanics and geological investigations that can be conducted either by an unmanned, self-propelled ELMS rover, or by an ELMS attached to a Martian Lander are discussed, along with the associated instrumentation.

Through such investigations, ascertaining the existence of some primitive forms of past or present life on Martian or Lunar geological formations may become possible, in addition to obtaining numerous data on the mechanical and physicochemical properties of Martian or Lunar soils along long traverses.

INTRODUCTION

As a spin-off of the Lunar Roving Vehicle (LRV), which operated very successfully on me lunar surface during the Apollo 15, 16, and 17 Missions (Costes *et al*., 1972), a novel mobility system designated as the "Elastic Loop Mobility System (ELMS)" was developed at Marshall Space Flight Center with the cooperation of the then Lockheed Missiles and Space Company, Huntsville, Alabama, and the U.S. Army Waterways Experiment Station (WES),Vicksburg, Mississippi. The ELMS has been assessed under a variety of testing modes and terrain conditions and its performance has indicated that in a low gravity environment it exceeds by far the performance capabilities of either the manned LRV or the unmanned, remotely controlled, self-propelled vehicles Lunokhod 1 and 2 which landed on the Moon aboard the then Soviet Spacecraft Luna 17 and 21 (Vinogradov, 1971).

For these reasons, at the request of the then Director of NASA Langley Research Center (Cortright, 1974), the ELMS became the candidate mobility system for a "1975" and a "1979" "Mobile Viking Mission" to Mars. Phase 1 studies showed that such a mobility system, which would have been attached to the main spacecraft, could sustain a free-fall landing on Mars and enable the spacecraft to traverse a distance of about 500 kilometers (Jackson, 1976) on the Martian surface, for a period of two years, without refurbishment of its consumables. These missions, however, did not materialize because of budgetary constraints.

With the renewed interest in Martian and Lunar Exploration, this paper will address ELMS performance characteristics and issues related to its design. However, the main emphasis of the paper will be put on soil mechanics tests and geological investigations that can be performed on Mars with the ELMS, drawing heavily upon the current experience from the Microgravity Experiment, "Mechanics of Granular Materials (MGM)", now in progress.

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MAJOR DESIGN FEATURES OF THE ELMS

About 64 years ago, an English inventor, J. K. Kitchen (Kitchen, 1933) proposed a continuous track, made of a highly elastic metallic material which would stiffen along the straight sections due to a pre-formed transverse curvature, as shown in Fig.1. This continuous and endless track eliminates several sources for friction and mechanical complexity, because no bogie wheels or track links are required. The tight fit between the rollers and the track poses a high risk for jamming and internal losses caused by the continuous crushing of foreign particles trapped between track and rollers. Attempts by Bendix to apply a continuous track concept to a small unmanned Surveyor Lunar Roving Vehicle (SLRV) were not successful (Moore *et al.*, 1970).

In the ELMS concept, the elastic loop performs a dual function, namely:

(1) It distributes the load over a large footprint, without bogie wheels, and
(2) It provides spring suspension, through the 180-degree bends of each loop as suspension springs (Figs. 2, 3, 4, and 5).

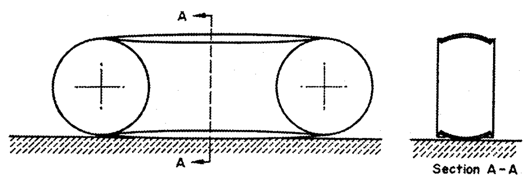

Fig. 1 Continuous track proposed by Kitchen [1933] is supported by two inner rollers.
(After Costes and Trautwein, 1973)

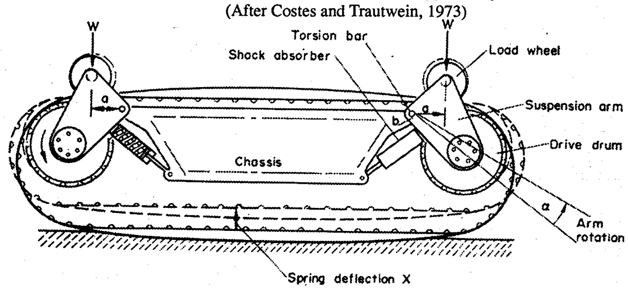

Fig. 2 ELMS concept. Vehicle weight transmitted by load wheel. Moment *Wa* keeps drive drum(s) in contact with loop. Spring deflection *X* causes arm rotation *a*.
(After Costes and Trautwein, 1973)

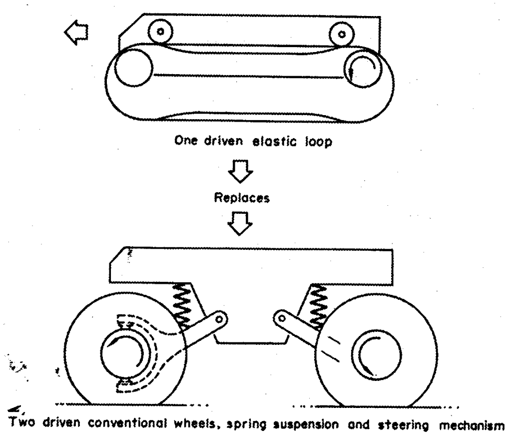

Fig. 3 Elastic loop concept simplifies vehicle design.
(After Costes and Trautwein, 1973)

Detailed description of the design and functional of the ELMS can be found elsewhere (Costes and Trautwein, 1972).

Single and multiple ELMS units (Figs. 6-11) underwent a thorough evaluation at the Mobility Facilities of the U.S. Army Waterways Experiment Station (WES) (Melzer and Trautwein, 1972; Melzer and Swanson, 1973). The system was tested on crushed-basalt lunar soil simulant (LSS) at two consistencies: one in which the LSS was placed air-dry and loosely compacted, thereby exhibiting high compressibility and low strength characteristics. In the second case, the LSS was placed moist and was compacted to attain a relatively high strength and resistance to penetration. These two consistencies were attained under carefully controlled conditions so as to allow direct comparison of the ELMS performance with that of the wire-mesh wheels of the LRV which had also been evaluated on the same LSS at the same Mobility Facilities (Costes *et al.*, 1973; Trautwein, 1972; Green and Melzer, 1971).

The results of these tests showed that ELMS performance on soft soil (loose, or compacted), is decisively superior to that of the LRV wire-mesh wheel.

On soft soil, the ELMS was capable of climbing 31-degree slopes, and on compacted, high-strength soil, 35-degree slopes. This was in contrast with 18-degree slopes that the LRV was ever able to climb during the Apollo 16 Mission (Mitchell *et al.*, 1972).

The maximum rigid-step height that could be negotiated by a remotely controlled, self-propelled ELMS model was 46 cm (Fig. 10). This height, as analyzed by Kuhner (Kuhner, 1935), exceeds the capabilities of a conventional track of the same geometry by almost 100 percent. Comparing the same height with the height of a wheel the diameter of which is the same as the height of an ELMS, shows an advantage of 3:1 for the ELMS capabilities over those of 4x2 wheeled vehicles; i.e., four-wheel vehicles with two power-driven wheels. The substantial advantage of ELMS is evident in the plot of results by Rettig and Bekker (Bekker, 1968), as shown in Fig. 7.

A 3x3 ELMS concept can cross crevasse widths in the range of 90 percent of the length of each ELMS unit, or 73 percent of its stowed length (Figs. 11 and 12). From the same tests, observations have also been made on the "Ride Quality" of the ELMS. Two factors contribute to the smooth ride of a vehicle: the first factor is the ratio of the "unsprung mass" of the running gear to the "sprung mass" of the vehicle, "um/smtr(Fig. 13). The second factor is the footprint developed by the running gear of the vehicle. In wheeled roving vehicles, the ratio "um/sm" is quite high (about 0.2), due to the electric drive and the steering assembly located in the wheel hubs. The ride quality is improved if the ratio "um/sm" is reduced. The only significant "unsprung mass" in ELMS units is the lower loop segment in contact with the ground, which is of the order of 10 percent of the vehicle mass. The motion of the drive motors which are suspended in the pivoting arms is small compared to the vertical spring deflection of the elastic loop.

Therefore, for average random ground excitations, the drive system can be considered to be a part of the vehicle "sprung" mass. By judicious material selection and design, the loop grousers, shown in Fig. 5, can perform, to some extent, the cushioning function of pneumatic tires. Regarding the second factor, the large footprint developed by the ELMS concept, which contributes to its superior slope-climbing capabilities and other performance characteristics of the vehicle on smooth soil surfaces, can also provide a beneficial effect on ride quality (Fig. 14).

Steering maneuvers on soil have shown that the input torque requirements to an ELMS vehicle increase with increasing yaw steering angle (up to 30 percent for yaw steering angles of 40 degrees). However, the maneuverability of a 3x3 ELMS vehicle is enhanced by differential speed control and/or steering of the front single ELMS unit lifted through an active pitch control system.

SOIL MECHANICS AND GEOLOGICAL INVESTIGATIONS ON MARTIAN OR PLANETARY SURFACES USING AN ELMS CONCEPT

Because of the proven superiority in its performance characteristics, the ELMS appears to offer substantial advantages for future Martian or other planetary exploration. Following are examples of such investigations through either a manned, or an unmanned, remotely controlled ELMS vehicle, or an ELMS mobility system attached to a Martian Lander (Fig. 15).

Being stable under lateral and overturning motion (Fig. 16), the ELMS appears to be an ideal platform for conducting surface and subsurface investigations on Mars or the Moon, using telescopic excavating tools for soil or rock sampling, or employing subsurface sounding or drilling devices to explore consolidated or unconsolidated "geological" materials. The surface and sub-surface soils (regolith) on Mars and the Moon appear to be very dense, which makes subsurface sampling and sounding very difficult, unless new techniques and tools are devised.

Knowledge of physico-chemical (including mechanical) soil properties are needed for safe and economical construction of both mechanical systems and human operations. To conduct the necessary science and engineering in support of robotics and manned missions, data to depths exceeding 1.5 m are needed, especially for constructing protective shelters.

A subsurface sounding device based on a vibration-assisted auger and cone penetrometer system will make it possible to obtain soil samples in situ that, in turn, can be studied optically, physically, or chemically by remotely controlled techniques.

Penetration resistance data can be analyzed to obtain basic strength (friction and cohesion) and stiffness properties. This information is needed to understand interactions between the soil (regolith) and mechanical/human systems, and to design future vehicles, shelters, or material beneficiation (mineral processing) facilities.

For relatively shallow, soft soil formations, a combination of penetrometer/shear vane instruments such as those used during the traverses of the Soviet unmanned rover Lunkhod 1 in the western part of Mare Imbrium on the Moon, as reported by Leonovich *et al* (Leonovich *et al.,* 1971) and Mitchell *et al.* (Mitchell *et al.,* 1972) can obtain a large number of measurements (327 obtained by Lunokhod in a traverse exceeding 5 km), while the vehicle is in motion. This would provide quantitative indication of soil property variations between different areas and depth.

Recent investigations using lunar soil simulants have shown that vibration-assisted drilling and insertion of anchor systems are feasible and efficient techniques (Klosky *et al.,* 1995, 1996;Jolly *et al.,* 1994) for both penetration and excavation. Effective soil penetration and excavation can be achieved by frequency modulated vibration at or near the soil-system's natural frequency to break cohesive or chemically cemented bonds, and loosen the soil matrix. Because the tools brought to the Martian or lunar surface will have a relatively small mass and will not be as robust as their counterparts on Earth, only through the use of a stable platform can such operations become feasible. As mentioned previously, a stable platform for making such operations feasible can be provided by the ELMS concept which can also allow the transport of data acquisition and transmission instruments.

The use of an auger-drill system will make possible detailed subsurface investigations of soil composition in addition to mechanical properties. The ELMS vehicle would in this case carry a mass spectrometer and other analytical devices which could also provide vital information regarding the existence of some form of primordial life on Mars or the Moon.

In conclusion, it should be noted that much of the information cited herein has been drawn from the personal involvement and experience of the Authors in the Apollo Program and the current, on-going Microgravity Experiment, "Mechanics of Granular Materials (MGM)".

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